NASA/TP—2007–215133

Optimization of Crew Shielding Requirement in Reactor-Powered Lunar Surface Missions

A.F. Barghouty
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

November 2007

The NASA STI Program Office…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320
  301–621–0390

NASA/TP—2007–215133

Optimization of Crew Shielding Requirement in Reactor-Powered Lunar Surface Missions

A.F. Barghouty
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

November 2007

Acknowledgments

The author thanks Drs. Michael Houts, Melissa Van Dyke, and Shannon Bragg-Sitton, all of NASA Marshall Space Flight Center, for their support. The author also thanks Ms. Katherine Harine (Raytheon Corp.) and Dr. David Poston (LANL) for making their simulation results available for this study prior to publication.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076–1320
301–621–0390

This report is also available in electronic form at
<https://www2.sti.nasa.gov>

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ALARA	as low as reasonably achievable
CME	coronal mass ejection
GCR	galactic cosmic rays
ICRP	International Commission on Radiological Protection
ISS	International Space Station
LEO	low Earth orbit
MeV	million electron volt
NCRP	National Commission on Radiation Protection
Q-Factor	radiation quality factor
SEP	solar energetic particle
SPE	solar particle event
Sv	Sievert

NOMENCLATURE

A	fitting constant (dose rate)
B	fitting constant (dose rate)
D	dose rate
D_s	safe dose rate
H	Hamiltonian
J	cost functional
α	optimization constant
c	control variable
$\in$	variational parameter
r	surface separation distance
ν	co-state variable (in the Hamiltonian)
β	optimization constant
λ	regolith attenuation coefficient
μ	state variable (in the Hamiltonian)
τ	optimization constant
x	regolith mass

TECHNICAL PUBLICATION

OPTIMIZATION OF CREW SHIELDING REQUIREMENT IN REACTOR-POWERED LUNAR SURFACE MISSIONS

1. INTRODUCTION

In addition to other flight risks and hazards, space flight beyond the confines of the Earth's magnetic field must face the challenges of space radiation exposure. In extended lunar surface missions, protection of crew and systems requires shielding strategies against various sources of space radiation fields, both natural and man-introduced. Due to various degrees of variability, unpredictability, and, in some critical areas, lack of basic data, guaranteeing safe levels of exposure poses a special challenge.

Exposure estimates for shielding solutions as well as for safety assessment must be formulated and optimized based on incomplete data, constrained by both technical and nontechnical factors. One of the more consequential constraints, albeit somewhat subjective, is that of "as low as reasonably achievable" (ALARA).

A main task of mission designers is to minimize requirements on structure and function while ensuring maximum protection for crew and systems, consistent with ALARA. ALARA is currently NASA's accepted guideline as well as being a part of the legal requirements with regard to ionizing radiation exposure and crew health and protection.

To be consistent with ALARA, shielding solutions and dose and risk assessments must rely on robust and accurate exposure estimates. Objective comparisons among these solutions will clearly require reliable estimates as well.

To various degrees, such estimates are hampered by inherent uncertainties in basic knowledge of the radiation environment itself, its transport and interaction in various media of complex geometry and composition, and most critically, in the human biological response to such exposure.

In the absence of more empirical data, on the one hand, and the increasing complexity of the modality and applications by which (and for which) these estimates are determined, on the other, such estimates are best viewed as guidelines rather then predictions.

Given the expected doses, this parametric study focuses on estimating the optimal crew shielding requirement in lunar surface missions with a nuclear option. Possible missions are assumed to take place during both low and high solar activity. Specificity due to the mission's location on the lunar surface is not taken into account. For this study's purposes, these missions are assumed to only include a crew habitation module that is powered by a small fission reactor placed at some distance from this module. No other details about the reactor or the habitation module, such as their geometric configurations and specific structures or subsystem, are either assumed or used.

Independent of the exact type or chemical composition of the shielding material, any shielding solution will require a certain amount of areal density to reduce the crew's expected exposure to acceptable levels. For this study, lunar regolith, albeit in an idealized form, is assumed to be the shielding material of choice.[1]

The estimates and method presented here are meant to help mission designers put in perspective the expected cumulative exposure—due to natural and introduced sources— vis-a-vis the amount of regolith mass required for crew protection. For example, for logistical considerations, it may be desirable to minimize the separation distance between habitat and reactor while maintaining maximum protection. Conversely, it may be desirable to minimize the amount of regolith to be used by maximizing the distance. Ideally, in both extremes, as well as for all estimates in between, required regolith mass must be optimized for each separation distance.

Since shielding will be required that can be used for both reactor and crew, a self-consistent approach would be to estimate, at a given distance, the optimal and also total amount of regolith mass separating the crew from the reactor. Because of the additive nature of the solution, this amount can be thought of as the sum of habitat and reactor shielding. This self-consistent solution should allow for more flexibility in allocating material resource and/or construction effort between reactor and habitat.

A brief survey of the radiation environment and exposure doses is presented, followed by a description of the dose-depth relations used and the one-dimensional optimization scheme. Sample results for optimized required regolith mass and reactor/crew separation for missions during solar minimum and maximum conditions, superimposed on a 'typical' large solar particle event, are provided, followed by a discussion and conclusions.

2. THE RADIATION ENVIRONMENT

Energetic, high-charge galactic cosmic-ray (GCR) ions and solar energetic particles (SEP) constitute the main (natural) source of this intense radiation environment. The energy range of these particles spans more than eight orders of magnitude (from thermal to ultra-relativistic) while their atomic numbers populate all of the stable nuclides of the periodic table.

Atomic charges of 1 (hydrogen) through 26 (iron), however, are considered important for crew radiation safety and shielding purposes. By number, hydrogen constitutes about 90%, helium, 7%, and all others, 3% of the GCR ions. The intensity of the ambient GCR component ($\approx$1 cm^{-2}) peaks around 500 MeV/nucleon and is modulated by a factor of about three over the 11-year solar cycle.[2] During solar maximum, and due to the actions of the solar wind, access to the heliosphere by diffusing GCR ions is reduced. As a result, the GCR component appears depressed in the inner heliosphere.

During heightened solar activities, solar particle events (SPE), while random in occurrence, are more frequent and are strong enough to transport SEPs, by a propagating shock driven by a coronal mass ejection (CME), to Earth's orbit and beyond. The SEP component is mostly composed of energetic protons, and it peaks around a few tens of MeV in energy, but can vary widely in intensity ($\approx 10^7$ cm^{-2}) as well as in the shape of its energy spectra. The so-called 'large' events, such as the October 1989 event, can be an order of magnitude more intense than the 'average' event, and many orders of magnitude above the quiescent conditions, lasting for hours to 2–3 days.[2]

Relatively little is known (or can reliably be predicted) about the photospheric, coronal, and heliospheric mechanisms responsible for CMEs and large SPEs. Furthering our basic understanding in these areas remains a key prerequisite[3] of the Exploration Vision.

In addition to these natural sources of space energetic particles, there are likely to be man-introduced radioactive and fission sources for power and even propulsion purposes as well. A number of studies[4,5] conducted for the power requirements during future lunar surface missions, for example, suggest that the need is on the order of tens of kilowatts of electric power.

For this level of power, chemical, solar, and radioisotope sources may be insufficient or impractical. For crew protection purposes, fission reactors are considered mainly as sources of energetic neutrons and gamma rays (photons). Contributions of these sources to the total expected crew dose are mostly due to prompt neutrons. Prompt neutrons are produced in the fission process of the fissile material, such as uranium-235 or plutoium-239. Most of these are energetic or 'fast' neutrons produced (at $\approx 10^{14}$ cm^{-2}) as direct fission products with an average energy of about 2 MeV. Photons (at $\approx 10^{10}$ cm^{-2}) are produced as both direct products of the fission reaction as well as a result of the subsequent decay of the fission radioactive products. For shielding purposes, however, gamma rays with energy $<$0.6 MeV are typically ignored.[6]

3. EXPECTED EXPOSURE LEVELS

Crew exposure levels are typically expressed in dose equivalent units. Dose equivalent, in Sievert (Sv) units, is calculated from the dose corrected by a dimensionless, multiplicative factor called the radiation 'quality factor', or Q-factor.[7] Ionizing radiation like energetic heavy ions (such as GCR ions) are characterized by high Q values. Uncharged neutrons are also assigned high Q values to underscore their more serious health hazards relative to either x rays or gamma rays at the same energy. Unlike the physically describable and measurable dose, the Q-factor is an empirical, dimensionless variable assumed to 'represent' the majority of the biological effects associated with exposure to ionizing radiation, but without specifying such effects by their end points or response functions.[8]

Estimating the health risk—and thus, shielding requirement—associated with space radiation exposure is hampered mostly by uncertainties in the biological response.[9] Other factors associated with the radiation environment and its physical interactions, as well as the dose and dose-rate volatilities, also contribute to the risk. As will be discussed later on, large (≈200%) uncertainties in the Q-factor can significantly affect shielding requirements, and any optimized estimates of which, as well.

The National Commission on Radiation Protection (NCRP) publishes and regularly updates recommended limits appropriate for low Earth orbits (LEO) missions. Table 1 lists the 1999 recommendations[10] for organ dose limits for all ages for 30-day, annual, and career exposures. (Note the 50-cSv limit for bone marrow.)

Table 1. 1999 NCRP recommended dose limits by organ and exposure duration.

Limit (cSv)	Bone Marrow	Eye	Skin
30-day exposure	25	100	150
Annual	50	200	300
Career	50–300	400	600

To put this 50-cSv limit and the other NCRP limits in perspective, on the International Space Station (ISS), for example, during solar maximum, the average effective dose was measured to be about 6.1 cSv, while the effective dose rate was about 0.037 cSv/day.[11] Note though that on the ISS, in addition to protective geomagnetic effects (which are not present outside the magnetosphere), shielding equivalent to about 5-10 cm of aluminum is provided by the ISS structure and system's materials.[12]

On the lunar surface, the dose due to the (isotropic) GCR source is reduced by a half due to the shadow shielding effect of the Moon itself. The introduction of a small nuclear fission reactor (≈25-kWe) is estimated[13] to add about 5 cSv/year at a 'safe distance' from its shielded core. Both water and regolith have been considered for core shielding.[13]

Table 2 contrasts typical expected[14,15] doses on the surface of the Moon with and without a 50-cm thick shield made of idealized lunar regolith, equivalent to 11 in of standard aluminum, assuming solar minimum GCR conditions and superimposed on an August 1972 class SPE. Given currently accepted limits for LEO missions (see table 1) these expected exposure figures clearly suggest that extended (>6 mo) surface missions will require shielding solutions, even without the presence of a nuclear fission source.

Table 2. Expected doses on the lunar surface with and without shielding (no nuclear power source assumed).

Duration (days)	GCR (cSv)	SEP (cSv)	Mission (cSv)
10	0.3/0.8	7.5/20.5	7.8/21.3
30	1/2.5	7.5/20.5	8.5/23
180	6/15	7.5/20.5	13.5/35.5
360	12/30	7.5/20.5	19.5/50.5

4. PARAMETERIZING THE DOSE-DEPTH RELATIONS

For the purpose of this parametric study, dose as a function of depth in lunar regolith from all three radiation sources, i.e., GCR, SEP, and fission sources (we ignore contribution from neutron albedo) will be assumed to have simple closed form expressions amenable to variational analysis. To that end, the GCR dose-depth relation is taken to be

$$D_1(x) = A_1 \exp(-\lambda_1 x) + B_1 \quad , \tag{1}$$

where $D_1(x)$ is the dose rate in cSv/yr, x is total regolith separation mass between reactor and crew in g/cm^2 (i.e., an arbitrary combination of reactor depth and habitat shielding) and λ_1 is the regolith attenuation coefficient for GCR in (g/cm^2)$^{-1}$.

The constants A_1 = 74 cSv/yr and B_1 = 28 cSv/yr, as well as λ_1 = 0.06 (g/cm^2)$^{-1}$ are estimated using fits to three-dimensional Monte-Carlo simulations assuming solar minimum conditions.[16] For solar maximum conditions, the values are: A_1 = 54, B_1 = –24, and λ_1 = 0.02.

For this approximation as well as for the other two below, lunar regolith is idealized as being composed of 74% oxygen, 11% silicon, 7% aluminum, 4% calcium, and 4% magnesium by weight. The density of this aggregate is taken to be 1.5 g/cm^3.

The GCR/SEP particle flux is transported through a thick slab of this idealized regolith, suffering both energy and charge losses. The transported flux is converted into dose and dose equivalent quantities using the International Commission on Radiological Protection (ICRP) 1991 conversion convention.[17]

The SEP transported flux is similarly assumed to be of a simple (analytic) form,

$$D_2(x) = \frac{A_2}{B_2 + \lambda_2 x} \quad , \tag{2}$$

where $D_2(x)$ is now the event integrated dose in cSv, A_2 = 400 cSv, B_2 = 1, and λ_2= 1.08 (g/cm^2)$^{-1}$. These numbers are based on three-dimensional transport simulations through a finite slab of lunar regolith as described above and for an assumed August 1972 class SPE.

The dose-depth approximation as a function of radial distance from the reactor's location is also based on three-dimensional transport simulations.[13] The conceptualized reactor in the simulation is a moderated spectrum, NaK cooled, Hastelloy™ (a Hayes International, Inc. product)/uranium-zirconium hybrid (UZrH) reactor with open lattice pin geometry.[18] The reactor provides thermal power to a 25-kWe Stirling engine power conversion system. The cylinder-shaped system (reactor, water shield, and power conversion system) stands ≈ 2 m high and is ≈1 m in diameter.

The reactor's transported[13] neutron and gamma rays fluxes are assumed to originate from a shielded core. To first order, the reactor's dose-depth relation for a given r (surface separation distance in m) can be approximated as

$$D_3(x) = \left(A_3 \exp(-\lambda_3 x) + B_3\right) \big/ r^2 \quad , \tag{3}$$

where $D_3(x)$ is the dose rate in cSv/yr, $A_3 = 2 \times 10^6$ cSv/yr-m^2, $B_3 = 3 \times 10^3$ cSv/yr-m^2, and $\lambda_3 = 1.87 \times 10^{-2}$ (g/cm^2)$^{-1}$.

5. OPTIMIZATION SCHEME

To formulate a one-dimensional variational scheme, equation (3) is re-expressed as a controllable, 'dynamical' system as:

$$\frac{\partial D_3}{\partial x'} = -D_3(x') + \frac{B_3}{r^2} c(x') \ , \tag{4}$$

where $x' = \lambda_3 x$ is the 'dynamical' variable, $c(x')$ is the control variable, and r is a parameter. The controllability of the process is assumed[19] based on the system being autonomous, linear, and possessing a stable, (uncontrolled) 'equilibrium' state as $x' \to \infty$.

The initial condition, $D_3(0)$, is taken to be the uncontrolled state at $x' = x = 0$ where the control variable c is identically equal to unity. Formulated this way, the objective becomes to find the optimal regolith mass, $x' = x^*$, such that for a given r the functional:

$$J\left[x^*(r)\right] = \int_0^{x^*(r)} \left[\tau + \frac{1}{2} c^2(x')\right] dx' \ , \tag{5}$$

is minimal while assuring a safe dose, i.e., $D_3(x^*) \leq D_s$.

An optimal solution is assumed to exist due to the convexity property of $J\,[x^*(r)]$, i.e., over its entire domain $\mathcal{D}$, $J(x')$ assumes a minimum value at each and every stationary point in $\mathcal{D}$. This property of J assures[20] that

$$J(x') \geq J(x^*) + \nabla J(x^*) \cdot (x' - x^*); \forall x', x^* \in \mathcal{D} \ , \tag{6}$$

where ∇J is the gradient of J.

The safe dose, D_s is taken to be the dose limit (an NCRP limit) including the contributions due to GCR and SEP exposure as a function of depth x'. The first term in this 'cost' functional J is taken to be solely determined by the total mass required, x^*, while the second term by the incremental amount of mass needed to reduce the incurred dose to its current level at this $x'(r)$ point.

The constant τ is a measure of this distribution between the two: When $\tau \gg 1$, this corresponds to a solution for achieving a safe dose level at a given r with as little regulation, i.e., r-manipulation, as possible. Conversely, when $\tau \ll 1$, the safe dose level is achieved for maximal manipulation (regulation). Note that no optimal solution exists when τ is identically zero.

The optimization proceeds by assigning a 'Hamiltonian' to the process according to the Pontryagin maximal principle.[19,21] The Hamiltonian remains constant along an optimal trajectory, $x' = 0 \rightarrow$ to $x' = x^*$. The general form for a one-dimensional Hamiltonian is:

$$H = \nu_0 \dot{\mu}_0 + \nu_1 \dot{\mu}_1 \ . \tag{7}$$

The μ variables are called state variables while the ν ones are called the costate variables (analogous to generalized coordinates and generalized momenta in analytical dynamics). Both sets are given by Hamilton equations of motion,

$$\dot{\nu}_0 = -\frac{\partial H}{\partial \mu_0} \, , \ \dot{\nu}_1 = -\frac{\partial H}{\partial \mu_1} \ , \tag{8}$$

$$\dot{\mu}_0 = +\frac{\partial H}{\partial \nu_0} \, , \ \dot{\mu}_1 = +\frac{\partial H}{\partial \nu_1} \ . \tag{9}$$

At each point along the optimal trajectory the Hamiltonian remains minimized. For this system,[21] i.e., equations (4) and (5), the Hamiltonian is:

$$H(x') = -\left[\tau + \frac{1}{2} c^2(x') \right] + \nu_1 \left[-D_3(x') + c(x') \right] \ . \tag{10}$$

Solving for ν_1 and c, and applying initial and safety conditions on D_3, gives the following transcendental relation for $x^*(r)$:

$$D_3(0)/D_r \exp x^* - D_s(x^*)/D_r - 2\beta \sinh x^* = 0 \ , \tag{11}$$

where $D_r = B_3/r_2$ and β is a constant of the 'motion.' Constants of the motion α and β are determined from the initial and safety conditions,

$$\beta = D_3(0) - \alpha/2 \ , \tag{12}$$

and where α is the negative root of:

$$\alpha^2 - 2\alpha D_3(0) - 2\tau = 0 \ . \tag{13}$$

The next step is to estimate the value of the constant τ for this particular optimization, equation (4), and the choice for the functional form of J, equation (5).

The directional derivative of J at c is defined as[20]:

$$\delta J(c;d) \equiv \lim_{\varepsilon \to 0} \left[\frac{J(c + \varepsilon d) - J(c)}{\varepsilon} \right] \tag{14}$$

$$= \frac{\partial J}{\partial \varepsilon}(c + \varepsilon d)\Big|_{\varepsilon=0} \quad . \tag{15}$$

From equation (5),

$$J(c + \varepsilon d) = \int_0^{x^*(r)} \left[\tau + \frac{1}{2}c^2 + \varepsilon cd + \frac{\varepsilon^2}{2}d^2 \right] dx' \quad . \tag{16}$$

Subtracting $J(c)$, dividing by ε, and taking the limit as $\varepsilon \to 0$, results in

$$\delta J(c;d) = \int_0^{x^*(r)} c(x')d(x')dx' \quad . \tag{17}$$

Now, from the convexity property of J,

$$\delta J(c;d) = \frac{\partial J}{\partial c} d \quad , \tag{18}$$

and from the symmetry property of equation (17) with respect to $c \leftrightarrow d$, and recalling that $c = 1$ corresponds to the uncontrolled, initial condition, results in

$$\partial J(c;1) = \partial J(1;c) = \frac{\partial J}{\partial x'} \left(\frac{\partial c}{\partial x'} \right)^{-1} \quad . \tag{19}$$

From the general solution of equations (4-11), it is known that $c(x') \propto \exp(x')$. It follows then, from the above relation, that, to within a constant of order unity, the numerical value of τ should be $\approx B_3$.

It should be noted that for this particular optimization scheme of equation (3), a different approach would have been to use the conditions on the Hamiltonian, i.e., minimal (including zero) and unchanged, along an optimal trajectory, rather than minimizing the cost functional J, as was done here. The alternate approach should, in principle, give the same results, but no attempt, for self-consistency, has been made here to demonstrate as much.

The first order, linear optimization scheme presented here should also be treated as parametrization specific in so far as the form of equation (3) is concerned, i.e., its x' and r-dependence and the treatment, for purposes of estimating the optimal path, $x' \to x^*$, of the variable x' as the 'dynamical' variable and r as being part of the control variable $c(x')$. No attempt has been made here to check for the applicability of the solution (controllability, existence, uniqueness, etc.) over wide ranges of the fit parameters, A_i, B_i, and λ_i. However, the theory of linear, first order control problems, such as the one described by equation (4), is well anchored, and properties of the general solutions are known for sufficiently large phase and parameter spaces, especially so for autonomous, one-dimensional systems.

The choice of the cost functional, equation (5), also affects the solution; convexity-wise only the simplest form of the functional, i.e., quadratic, was used. Clearly, and as is discussed below, other forms must be explored as well. Finally, generalization of linear-state control problems to two and three dimensions is, in principle, straightforward. However, issues related to uniqueness and stability of the controlled solution become more critical in higher dimensions.[21] Generalization of this particular optimization scheme to higher dimensions must be preceded by further numerical and analytical demonstrations of its wider applicability and utility.

6. SAMPLE CALCULATION AND DISCUSSION

The optimization scheme demonstrated above is applied to two mission scenarios: one during GCR solar-maximum conditions superimposed on an August 1972 class SPE (figure 1), and the second is done similarly for GCR solar-minimum conditions (figure 2). (Note that 'depth' in the figures refers to the total regolith mass, in g/cm^2, separating reactor from crew.)

In both cases, the shielding material is the idealized lunar regolith as described in section 4, along with the parameterized forms and values of the transported radiation sources for each scenario. For each scenario, equations (4-11) are solved using the fit (A_i, B_i, and λ_i) and optimization (α_i, β_i, and τ_i) parameters, self-consistently. These latter ones depend sensitively on initial conditions and hence they change from one scenario to the other. The dose limit, for reference, is taken to be the 50-cSv/yr level, i.e., the LEO 1999 NCRP annual limit for bone marrow exposure (table 1).

For each scenario, as a function of distance from the reactor, shown in the figures is the optimized total (due to reactor plus natural) mass of lunar regolith required to keep the dose rate level less than or equal to the safe rate of 50 cSv/yr. Also shown is the required mass for the reactor-only case, i.e., no GCR or SEP fields assumed, and for the natural environment-only case, i.e., no reactor. After subtracting the mass requirement to shield against the GCR and SEP fields, the balance can, as mentioned earlier, be treated as an arbitrary combination of both the amount of shielding required for the reactor plus that for added shielding, due to the introduction of the reactor, for the habitat.

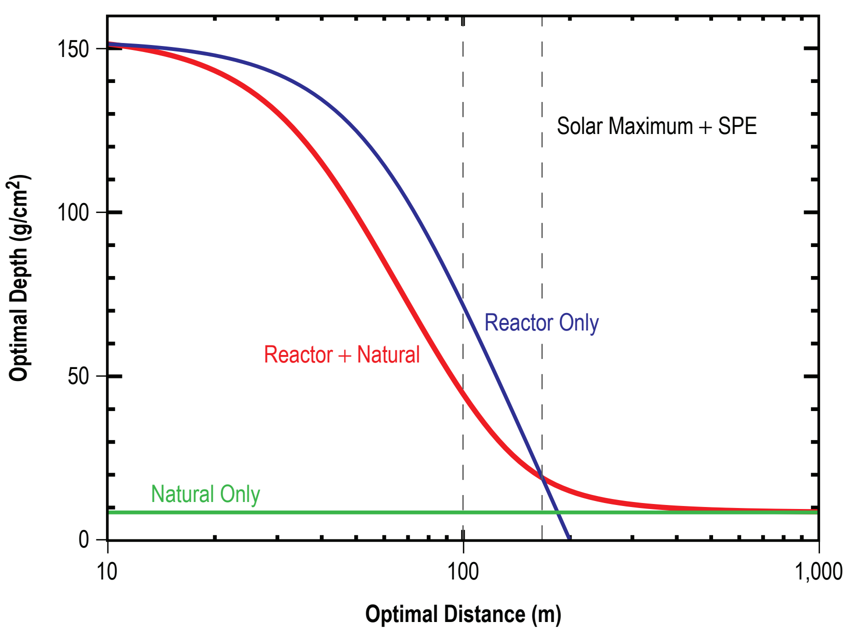

Figure 1. Optimized reactor depth-distance solution for GCR solar maximum conditions superimposed on an August 1972 class SPE, for a 50-cSv/yr dose limit (see table 1).

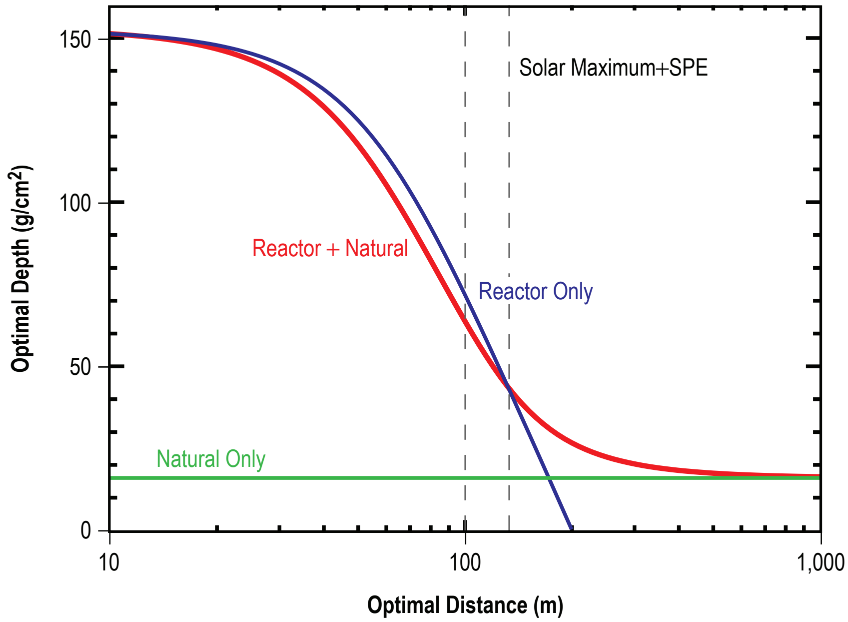

Figure 2. Optimized reactor depth-distance solution for GCR solar minimum conditions superimposed on an August 1972 class SPE, for a 50-cSv/yr dose limit (see table 1).

For example, for a surface mission during solar minimum, at a distance of 100 m from the reactor, from figure 2, the optimized total regolith shielding requirement is about 62 g/cm^2. Shielding against GCR and SEP fields requires about 16 g/cm^2. Note that the un-optimized reactor requirement (which is also the total here because it is larger than the natural overburden) is about 76 g/cm^2, which is a 23% savings in required mass due only to optimization. (For solar maximum conditions, figure 1, the savings are, of course, even larger (30–35%) because the natural environment overburden is lower.)

In addition, the 46-g/cm^2 requirement can be divided in a number of ways depending on other factors, such as availability and processing of regolith and reactor site preparation, between the actual required depth of the reactor system beneath the lunar surface and the actual thickness of the added habitat protection against the reactor's radiation fields. This added flexibility is a result of treating the reactor and habitat shielding requirements self-consistently in this simple optimization scheme.

However, this self-consistent treatment is also reflected in the optimization cost. In figure 2, for example, and for distances larger than about 133 m from the reactor, the 'optimized' mass is larger than what is actually required. The reason being the 'cost' of optimizing the mass for any distance is always nonzero, as can be seen from equation (5). In this particular optimization scheme, the optimization becomes 'cost-ineffective' for large distances, but not large enough, i.e., for distances at which the reactor's fields become negligible compared to the natural overburden (≈220 m for this study). Clearly, a more robust form for the cost functional, equation (5), is required to reduce the cost over a wider range of separation distance.

Also, the above assessment was based on an idealized regolith and its simulated attenuation properties against both natural and fission radiation sources. If one allows for an error margin of the same order in the attenuation properties of regolith (and not in its other physical properties[22]), this savings all but disappears. Imprecision in basic regolith attenuation properties that is on the order of 50–75% will render any optimization scheme frivolous.

It is important to note that variations in regolith density alone, which has a range of 1.5–2.8 g/cm^3, can easily contribute to this level of imprecision. When coupled with uncertainties in modeling the radiation quality factor, it becomes clear that this and similar optimization schemes are easily defeated by such large variabilities. Unfortunately, some of these variabilities are inherent to shielding and radiation protection studies associated with crewed lunar surface missions, with or without a nuclear option.

7. CONCLUSIONS

A parametric study was conducted to afford mission designers first order estimates for the amount of lunar regolith required to protect the crew on a lunar surface mission from exposure to GCR, SEP, and neutron fields associated with a small fission reactor.

Since shielding is expected to be required for both reactor and crew, a self-consistent approach was taken to estimate, at a given distance, the optimal (total) amount of regolith separating crew from reactor. The additive nature of the solution in this treatment should allow for some flexibility in allocating material resource and/or construction effort between reactor and habitat.

Simple but simulation based dose-depth relations were used for all three radiation sources in a one-dimensional optimization scheme. The objective was to estimate the optimal regolith mass between crew and reactor, as a function of their separation distance. The optimization scheme was based on Pontryagin maximal principle.

The scheme was applied to both solar maximum and minimum conditions. Depending on the mission's time profile, a savings of up to 30% in mass can be realized between optimized and un-optimzed required regolith mass estimates. However, it is argued that variation and uncertainty mainly in lunar regolith attenuation properties and in the radiation quality factor can easily defeat this and any other similar optimization scheme.

REFERENCES

1. Houts, M.G., Poston, D.I.; Trellue, H.R.; Baca, J.A.; et al.: "Planetary Surface Reactor Shielding Using Indigenous Materials," *Proceedings of Space Technology and Applications International Forum* (STAIF 1999), *American Institute of Physics Conference Proceedings 458,* edited by M.S. El-Genk, 1750 pp., Melville, NY, 1999.

2. Kudala, K.; Storini, M.; Hofer, M.Y.; and Belov, A.: "Cosmic Rays in Relation to Space Weather," *Space Science Reviews*, 93, pp. 153–174, 2000.

3. National Research Council, *Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop,* 104 pp., National Academy Press, Washington, D.C., 2006.

4. Kerslake, T.W.: "Electric Power System Technology Options for Lunar Surface Missions," *NASA/TM—2005–213629*, NASA Lewis Research Center, Cleveland, OH, April, 2005, Maryland, 2005.

5. Davis, J.M; Cataldo, R.L.; Soeder, J.F.; Monzo, M.A.; and Hakimzadeh, R.: "An Overview of Power Capability Requirements for Exploration Missions," *NASA/TM—2005–213600*, NASA Lewis Research Center, Cleveland, OH, April, 2005.

6. Angelo, J.A., Jr. and Buden, D.: *Space Nuclear Power*, 286 pp., Orbit Books, Krieger Publishing Company, FL, 1985.

7. Alpen, E.L.: *Radiation Biophysics*, 2nd. ed., 484 pp., Academic Press, San Diego, CA, 1998.

8. International Commission on Radiological Protection, ICRP Publication No. 92, *Relative Biologcal Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (wR)*, 80 pp., Elsevier, London, England, 2003.

9. Cucinotta, F.A.; Kim, M.-H.Y.; and Ren, L.: "Managing Lunar and Mars Mission Radiation Risks Part I: Cancer Risks, Uncertainties, and Shielding Effectiveness," *NASA—TP–2005-213164*, NASA Johnson Space Center, Houston, TX, May, 2005.

10. National Council on Radiation Protection's Report No. 98, *Update on Guidance on Radiation Received in Space Activities*, National Council on Radiation Protection, Maryland, 1999.

11. Cucinotta, F.A.: "Report on ISS Crew Quarter Shielding Improvements: ISS Increment-6," ISSP Program Integration Control Board, Johnson Space Center, Houston, TX, July, 30, 2003.

12. National Research Council: *Radiation and the International Space Station: Recommendations to Reduce Risk*, National Academy Press, Washington, D.C., 2000.

13. Poston, D.I., Ade, B.J., Pratap, S.; Leichliter, K.J.; and Dixon, D.D.: "Water and Regolith Shielding for Surface Reactor Mission," *Proceedings of Space Technology and Applications International Forum (STAIF-2006), American Institute of Physics Conference Proceedings, 813,* edited by M.S. El-Genk, pp. 953–966, Melville, NY, 2006.

14. Barghouty, A.F. and Thibeault, S.A.: "The Exploration Atmospheres Working Group's Report on Space Radiation Shielding Materials," *NASA—TM–2006-214604,* NASA Marshall Space Flight Center, AL, September, 2006.

15. Wilson, J.W.; Miller, J.; Konradi, A.; and Cucinotta, F.A. (eds.): "Shielding Strategies for Human Space Exploration," NASA Conference Publication 330, Langley Research Center, Hampton, VA, 1997.

16. Harine, K.J.: "Lunar Combination Radiation Transport Study," Raytheon Corporation Report ESTGSG-FY06-0163, unpublished.

17. International Commission on Radiological Protection, *ICRP Publication No. 60: Recommendations of the International Commission on Radiological Protection,* 215 pp., Pergamon Press, Oxford, England, 1991.

18. Dixon, D.D.: "Design of a 25-KWe Surface Reactor System Based on SNAP Reactor Technologies," *Space Technology and Applications International Forum (STAIF-2006), American Institute of Physics Conference Proceedings, 813,* edited by M.S. El-Genk, 932 pp., Melville, NY, 2006.

19. Cesari, L.: *Optimization Theory and Applications: Problems with Ordinary Differential Equations,* 542 pp., Springer-Verlag, New York, NY, 1996.

20. Troutman, J.L.: *Variational Calculus and Optimal Control: Optimization with Elementary Convexty,* 484 pp., Springer-Verlag, New York, NY, 1996.

21. Hocking, L.M.: *Optimal Control: An Introduction to the Theory with Applications,* 268 pp., Oxford University Press, USA, 1991.

22. Sibille, L.; Carpenter, P., Schlagheck, R.; and French, R.A.: "Lunar Regolith Simulant Materials: Recommendations for Standardization, Production, and Usage," *NASA—TP–2006-21460*, NASA Marshall Space Flight Center, AL, December, 2005.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 2007	Technical Publication

4. TITLE AND SUBTITLE
Optimization of Crew Shielding Requirement in Reactor-Powered Lunar Surface Missions

5. FUNDING NUMBERS

6. AUTHORS
A.F. Barghouty

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER
M–1208

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TP—2007–215133

11. SUPPLEMENTARY NOTES
Prepared by the Science and Exploration Research Office

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 93
Availability: NASA CASI 301–621–0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
On the surface of the moon—and not only during heightened solar activities—the radiation environment is such that crew protection will be required for missions lasting in excess of six months. This study focuses on estimating the optimized crew shielding requirement for lunar surface missions with a nuclear option. Simple, transport-simulation based dose-depth relations of the three radiation sources (galactic, solar, and fission) are employed in a one-dimensional optimization scheme. The scheme is developed to estimate the total required mass of lunar regolith separating reactor from crew. The scheme was applied to both solar maximum and minimum conditions. It is shown that savings of up to 30% in regolith mass can be realized. It is argued, however, that inherent variation and uncertainty—mainly in lunar regolith attenuation properties in addition to the radiation quality factor— can easily defeat this and similar optimization schemes.

14. SUBJECT TERMS
space radiation exposure, lunar habitat, shielding materials, shielding optimization, in situ materials, lunar regolith, nuclear surface power, ALARA

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

National Aeronautics and
Space Administration
IS20
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812